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Editor

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ELECTRONICS AND ELECTRICAL ENGINEERING

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Foreword

The purpose of EEEC-14 is promoting the creativity of the Chinese nation in the scope of Electronics and Electrical Engineering. Electronics, as well as Electrical Engineering are always the companion of Electrical and Electronics.

When we were collecting the papers for the Conference on Electronics and Electrical Engineering, the interesting things were that a number of authors were quite keen to look for the same chance to make public the theoretical works of intellectual creativity or formal results of scientific research or practice, written by those who are their former class mates, campus fellows, friends, relatives, colleagues and cooperators. It is really a chance for us to organize a chance for our smart intellectuals to expose, exchange and confidently approve each other and the value of their arduous work.

Electronics is one of the most important matters of our life and with us as ever we have existed, unlike computer or information technology but unfortunately we have never known all Electronics we have used around us. Nevertheless, we have been working very hard to discover new sources of energy we are in need of and striving non-stop for new synthetic stuffs or man-made matters. High demand has pushed our scholars, experts and professionals to continue the mission, not only for the materials themselves but non-perilous to the life and environment as well, causing the least hazard to the world. We appreciate our authors consciously to involve into that mission.

Asia-Pacific Electronics and Electrical Engineering Conference was scheduled to hold in Shanghai from December 27–28, 2014; experts and scholars, a group of the authors and other related people have attended the conference with apparent interest; we are expecting a full success of the conference.

We appreciate those who responded to our proposal and submitted their papers, especially those whose papers have been selected for the conference EEEC-14, the sponsors who have provided their valuable and professional suggestions and instructions and the scholars and professors who have spent their efforts as peer reviewers.

Thank you!
Samson Yu
December 1, 2014

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Fuzzy based direct torque and flux control of induction motor drives

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ABSTRACT: This paper investigates direct torque and flux control of an induction motor drive based on the Fuzzy Logic (FL) control technique. Direct torque and flux control has become a widely acceptable alternative to field oriented control The hysteresis-band controller for the stator flux and the electro-magnetic torque was designed using a Fuzzy Logic System. (FLS) in MATLAB. Simulation results show that the direct torque and flux control using an FL approach performs very fast dynamic response and has a simple structure which makes it to be more popularly used in the industry.

1 INTRODUCTION

Induction Motor (IM) drives may be classified into two main control strategies. Scalar control, of the IM voltage magnitude and frequency, is one of ac drives which produces good steady-state performance but poor dynamic response. There is an inherent coupling effect using the scalar control because both torque and flux are the functions of voltage or current and frequency. This results in sluggish response and is prone to instability because of 5th order harmonics. However, vector control (VC) decouples these effects.

A second IM drive method can be either the field oriented control (FOC) or the direct torque and flux control (DTFC or DTC). The principle used in these drive methods is to asymptotically decouple the rotor speed from the rotor flux in vector controlled ac motor drives. The two most commonly used methods of the vector control are direct vector control and indirect vector control. Control with field orientation may either refer to the rotor field, or to the stator field, where each method has own merits [1].

Direct torque and flux control is also denoted as direct self-control (DSC) which is introduced for voltage-fed pulse-width-modulation (PWM) inverter drives. This technique was claimed to have nearly comparable performance with vector-controlled drives [2]. Another significance mentioned in [3] is that DTFC does not rely on machine parameters, such as the inductances and permanent-magnet flux linkage. Consequently, a number of research approaches have been proposed for a wide range of industrial applications where [3] is proposed for direct-drive PMSG wind turbines.

If an IM is being operated under its steady state, the three-phase drive can be easily presented as just one-phase because all the variables on the IM are sinusoidal, balanced and symmetrical. However, if the operation requires dealing with dynamics of motor speeds or varying torque demands in a sudden change, the motor voltages and currents are no longer in a sinusoidal waveform. Hence, the IM drive scheme using vector control or direct torque and field control is able to provide faster transient responses due to these dynamics.

This paper is arranged as follows. Section 2 lists the notations used in this paper. Section 3 explains the induction motor dynamics. Section 4 describes the direct torque and flux control. Section 5 presents the design of the fuzzy logic controller. Section 6 illustrates the performance of the controller in the simulation. Specific conclusions are drawn in Section 7.

2 NOMENCLATURE

d^e-q^e synchronous reference frame direct, quadrature axes
d^s-q^s stationary reference frame direct, quadrature axes
u_{sd}; u_{sq} stator voltages
i_{sd}; i_{sq} stator currents
u_{rd}; u_{rq} rotor voltages
i_{rd}; i_{rq} rotor currents
ψ_s; ψ_r stator, rotor flux vector
R_s; R_r stator, rotor resistance
L_s; L_r stator, rotor self-inductance
Lm magnetizing inductance
σ resultant leakage constant
ω_e; ω_r synchronous, rotor speed
P number of motor pole pairs
J Total inertia
T_e; T_L electromagnetic, load torque

3 INDUCTION MOTOR DYNAMICS

3.1 *Machine model in arbitrary reference frames*

In a three-phase ac machine, there are three main reference frames of motion, which could be used to model

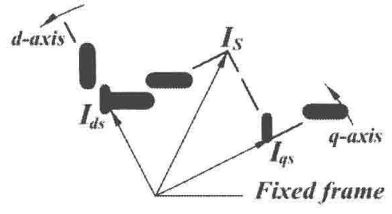

Figure 1. Reference frame of motion in an ac machine.

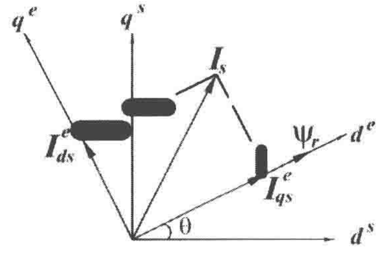

Figure 2. Decoupling between rotor flux and torque.

its three main regions of operation. These are the stationary reference frame for startup, the synchronous reference frame for equilibrium motion, and the rotor reference frame for changing speeds by acceleration or deceleration. The two commonly employed coordinate transformations with induction machines are the stationary and the synchronous reference frames as shown in Fig. 1.

In special reference frames, the expression for the electromagnetic torque of the smooth-air-gap machine is similar to the expression for the torque of a separately excited dc machine.

These mathematical transformations of rotor ABC variables to rotor d-q variables, which are known as Park Transformation [4], can facilitate understanding of the variation of the mutual inductance between the stator and the rotor under differing rotation conditions.

All the transformation equations from ds – qs frame to de – qe frame, and vice verse, remain the same as in an induction motor. The complex stator current space vectors sq and isd are defined as:

$$\begin{aligned} i^s_{qs} &= \frac{2}{3}i_{as} - \frac{1}{3}i_{bs} - \frac{1}{3}i_{cs}; \\ i^s_{ds} &= \frac{1}{\sqrt{3}}(i_{cs} - i_{bs}). \end{aligned} \tag{1}$$

A dc motor-like electromechanical model can be derived for an ideal vector-controlled drive in the d-q co-ordinate. One of the advantages of the separately excited dc motor of being able to decouple the flux control and the torque control that is thereby opened up. Fig. 2 shows this concept that the rotating vectors are orthogonal, but decoupled.

3.2 *Modeling of an induction motor in d–q co-ordinate*

The mathematical model [5] of an induction motor in d–q reference frame can be written as the stator voltage differential equations (2):

$$\begin{aligned} u_{sd} &= R_s i_{sd} + \frac{d}{dt}\psi_{sd} - \omega_e \psi_{sq}; \\ u_{sq} &= R_s i_{sq} + \frac{d}{dt}\psi_{sq} + \omega_e \psi_{sd}. \end{aligned} \tag{2}$$

And the rotor voltage differential equations (3):

$$\begin{aligned} u_{rd} &= 0 = R_r i_{rd} + \frac{d}{dt}\psi_{rd} - (\omega_e - \omega_r)\psi_{rq}; \\ u_{rq} &= 0 = R_r i_{rq} + \frac{d}{dt}\psi_{rq} + (\omega_e - \omega_r)\psi_{rd}. \end{aligned} \tag{3}$$

These linked fluxes of stator and rotor are as follows:

$$\begin{aligned} \psi_{sd} &= L_s i_{sd} + L_m i_{rd}; \\ \psi_{sq} &= L_s i_{sq} + L_m i_{rq}; \\ \psi_{rd} &= L_r i_{rd} + L_m i_{sd}; \\ \psi_{rq} &= L_r i_{rq} + L_m i_{sq}. \end{aligned} \tag{4}$$

Since the direction in d-axis is aligned with the rotor flux this means that the q-axis component of the rotor flux space vector is always zero.

$$\psi_{rq} = 0 \quad \text{and} \quad \frac{d}{d_t}\psi_{rq} = 0. \tag{5}$$

The slip frequency ω_{sl} can be calculated from the reference values of stator current components are defined in the rotor flux oriented reference frame as follows:

$$\omega_{sl} = \omega_e - \omega_r \tag{6}$$

We can calculate the rotor speed from the relation $\omega_r = \omega_e - \omega_{sl}$, since ω_{sl} and ω_e can be determined as [6]:

$$\begin{aligned} \omega_{sl} &= \frac{(1 + \sigma\tau_r s)L_s i_{qs}}{\tau_r(\psi_{ds} - \sigma L_s i_{ds})}; \\ \omega_e &= \frac{(V^s_{qs} - i^s_{qs}R_s)\psi^s_{ds} - (V^s_{ds} - i^s_{ds}R_s)\psi^s_{qs}}{{\psi_s}^2}. \end{aligned} \tag{7}$$

Here τ_r is the rotor time constant denoted as $\tau_r = \frac{L_r}{R_r}$, and σ is a resultant leakage constant defined as:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$

The state equations of a linear model for the induction motor dynamics can be obtained as:

$$\dot{x}=\begin{bmatrix} -\frac{(L_r^2R_s+L_m^2R_r)}{\sigma L_sL_r^2} & 0 & \frac{L_mR_r}{\sigma L_sL_r^2} & \frac{L_m\omega_r}{\sigma L_sL_r} \\ 0 & -\frac{(L_r^2R_s+L_m^2R_r)}{\sigma L_sL_r^2} & -\frac{L_m\omega_r}{\sigma L_sL_r} & \frac{L_mR_r}{\sigma L_sL_r^2} \\ \frac{L_mR_r}{L_r} & 0 & -\frac{R_r}{L_r} & -\omega_r \\ 0 & \frac{L_mR_r}{L_r} & \omega_r & \frac{R_r}{L_r} \end{bmatrix} x+\begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} \quad (8)$$

$$x=[i_{sd} \quad i_{sq} \quad \psi_{rd} \quad \psi_{rq}]^T$$

However, induction motors belong to a class of multi-variable nonlinear systems which could lead to the control task to be rather complicated due to to unknown disturbances (load torque) and changes in values of parameters during its operation. Such a challenge have been stated in hybrid vector control or DTFC induction motor drives [6]–[10].

The electromagnetic torque equation can be written as:

$$\begin{aligned} \bar{T}_e &= \frac{3}{2}(\frac{P}{2})\bar{\psi}_s \times \bar{I}_s \\ &= \frac{3}{2}(\frac{P}{2})\frac{L_m}{L_rL_s}\bar{\psi}_r \times \bar{\psi}_s \end{aligned} \quad (9)$$

Thus, the magnitude of the torque is

$$T_e = \frac{3}{2}(\frac{P}{2})\frac{L_m}{L_rL_s} \mid \psi_r \mid \mid \psi_s \mid \sin\theta_{sr} \quad (10)$$

where $\theta_{sr} = \theta_s - \theta_r$ is the angle between the stator flux and the rotor flux.

If the rotor flux remains constant and the stator flux is incrementally changed by the stator voltage $V^{-}s \times \Delta t$ with the corresponding angle change of $\Delta\theta_{sr}$, the incremental torque is then obtained as:

$$\Delta T_e = \frac{3}{2}(\frac{P}{2})\frac{L_m}{L_rL_s} \mid \psi_r \mid \mid (\bar{\psi}_s + \Delta\bar{\psi}_s) \mid \sin\Delta\theta_{sr} \quad (11)$$

The mechanical speed of the rotor in terms of the load constants can be computed as:

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_L \quad (12)$$

4 STUDY ON DIRECT TORQUE AND FLUX CONTROL

4.1 *Space vector modulation of 3-phase voltage source in-verter with DTFC*

During the IM drive operation, a control strategy for the voltage-fed space vector pulse-width-modulation (SVPWM) may be required with direct torque and field control. The structure of a typical 3-phase power inverter is shown in Fig. 3, where V_A, V_B and V_C are the voltages applied to the star-connected motor windings, and where V_{DC} is the continuous inverter input voltage.

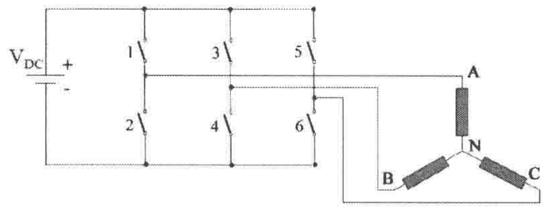

Figure 3. Basic scheme of 3-phase inverter connected to an AC motor.

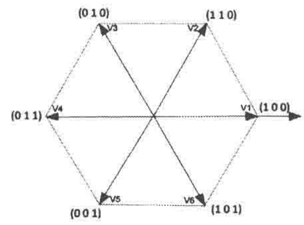

Figure 4. SVPWM voltage vectors

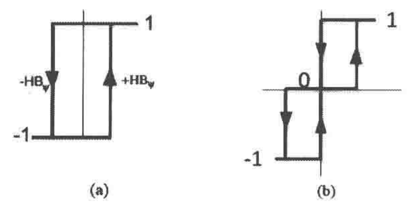

Figure 5. (a) Two-level stator flux hysteresis-band. (b) Three-level stator torque hysteresis-band.

The SVPWM method of generating the pulsed signals fits the above requirements and minimizes the harmonic contents. The inverter voltage vectors provide eight possible combinations for the switch commands. These eight switch combinations determine eight phase voltage configurations. SVPWM supplies the ac motor with the desired phase voltages. A diagram in Fig. 4 depicts these combinations.

4.2 *Control strategy of DTFC*

The magnitudes of command stator flux $\hat{\psi}_s^*$ and T_e^* are compared with the respective estimated values, and the errors are processed through the hysteresis-band (HB) controllers, as shown in Fig. 5.

The circular trajectory of the command flux vector $\hat{\psi}^*$ with the hysteresis-band rotates in an anticlockwise direction. The flux hysteresis-band controller has two levels of digital output according to the following relations [2]:

$$\begin{aligned} H_\psi &= 1 \qquad \text{for } E_\psi > +HB_\psi \\ H_\psi &= -1 \qquad \text{for } E_\psi < -HB_\psi \end{aligned} \quad (13)$$

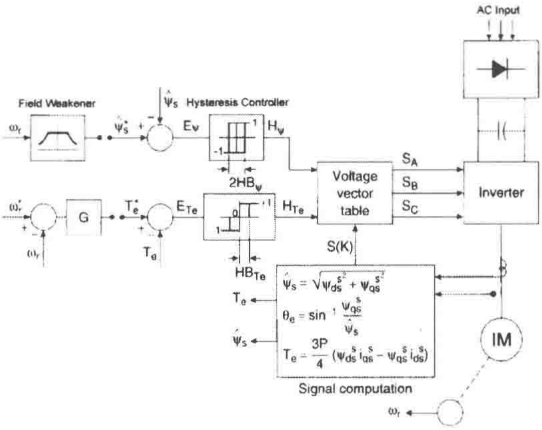

Figure 6. Block diagram of direct torque and field control.

Table 1. Switching table of inverter voltage vectors.

H_ψ	H_{Te}	S_1	S_2	S_3	S_4	S_5	S_6
1	1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_7	V_0	V_7	V_0	V_7
	−1	V_6	V_1	V_2	V_3	V_4	V_5
−1	1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_7	V_0	V_7	V_0	V_7	V_0
	−1	V_5	V_6	V_1	V_2	V_3	V_4

Also, a torque controller proportional gain is chosen by G = 1.5. The overall control of the DTFC is shown in Fig. 6.

When the inverter voltage sequence $V_1 - V_6$ is properly selected as shown in Fig. 4, the stator flux rotates at the desired synchronous speed within the specified band. As the stator resistance is small enough to be neglected, we may consider that the stator flux monotonically follows the stator voltage at each step time Δt.

Thus, changing the stator flux space vector can be accomplished by changing the stator voltage during a desired period of time which can be expressed as follows:

$$\bar{V}_s = \frac{d}{dt}(\bar{\psi}_s) \quad \Rightarrow \quad d\bar{\psi}_s = \bar{V}_s dt; \qquad \text{Thus,} \quad \Delta\bar{\psi}_s = \bar{V}_s \Delta t \tag{14}$$

Depending on the sector that the voltage reference in Fig. 4, two adjacent vectors are chosen. The binary representations of two adjacent basic vectors differ in only one bit from 000 to 111. This means the switching pattern moves from one vector to the adjacent one. The two vectors are time weighted in a sample period T to produce the desired output voltage to the inverter.

Table 1 applies the selected voltage vectors, which essentially affects both the flux and torque simultaneously.

Table 2. Flux and torque variations due to applied voltage vectors.

Voltage Vector							V_0 or V_7
	↑			↓			0
			↑			↓	↓

Table 2 shows the effect of the voltage vectors on the stator flux and the electromagnetic torque, which the arrows indicate the magnitudes and directions [2].

5 DESIGN OF THE FUZZY LOGIC CONTROLLER

5.1 *Structure of fuzzy control in DTFC*

Fuzzy logic has been widely applied in power electronic systems. Recently developed approaches in DTFC [11]–[13] have been proven to be more robust and improved performance for dynamic responses and static disturbance rejections using fuzzy logic control. [11] also designs a hysteresis-band controller in DTFC using a fuzzy logic method, but their fuzzy controller appears not precise enough because of the less membership functions being chosen.

Now a fuzzy logic controller is considered for the stator flux $\hat{\psi}^*$ and torque T^* of the DTFC induction motor drive.The fuzzy inference system (FIS) onsists of a formulation of the mapping from a given input set of E and CE to an output set using FL Mamdany type method in this study.

According to the switching table of the inverter voltage vectors, the triangular membership functions (MF) of the seven linguistic terms for each of the two inputs $e(pu)$ and $ce(pu)$ are defined in per unit values. $du(pu)$ is the output of the fuzzy inference system. Here, $e(pu)$ is selected as the flux error $\hat{\psi}^* - \hat{\psi}_s$ for the difference between the command stator flux and the actual stator flux ψ_s, and $ce(pu)$ is the rate of change of $\frac{d}{dt}\Delta\hat{\psi}_s$. The represented linguistic variables in the fuzzy rule matrix are:

NB = negative big NM = negative medium
NS = negative small Z = zero
PS = positive small PM = positive medium
PB = positive big

The general considerations in the design of the proposed fuzzy logic controller for this DTFC are:

1) If both $e(pu)$ and $ce(pu)$ are zero, then maintain the present control setting $du(pu) = 0$ (V_0/V_7).
2) If $e(pu)$ is not zero but is approaching to this value at a satisfactory rate, then maintain the present control setting of the voltage vector.